A Review of the Multicriteria Decision Analysis Applied to Oil and Gas Decommissioning Problems

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Abstract

Regardless of the economic activity, decommissioning decisions are often highly complex. This is due to the diversity of operational and local parameters, as well as the multitude of stakeholders involved, who generally have conflicting interests. This sets up a challenging multi-criteria decision problem on the activities to be carried out during the decommissioning process. This paper aims to present an overview of decision-support tools applied to decommissioning, and covers many economic sectors, with a focus on the oil and gas sector and on multi-criteria decision analysis (MCDA) methods. The paper delves deep into the aspects to be considered before reaching a decision, examining the experiences and methods found both in industrial reports and in academic papers.

Keywords: Decommissioning, Oil & Gas, Decision analysis, Multi-criteria decision analysis, Bibliographic review

1. Introduction

Decommissioning can be deemed the last phase of the life cycle of a project. In many cases, it can also be seen as the reverse of the installation process [161]. It essentially consists in the deactivation of an enterprise, which often occurs because the enterprise is no longer economically viable. Decommissioning activities are carried out in many economic sectors.

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One can decide, for instance, to deactivate a highway [154; 160], a nuclear plant [149; 147], a solar power generation facility [58; 144], or a mining complex [7; 100; 36], among other enterprises. This paper is particularly interested in the decommissioning process of oil and gas production facilities [e.g., 30; 107; 50; 61].

Generally, the alternatives available for decommissioning activities are limited by regulators and organizations. In addition, one may find various guidelines that should be followed, depending upon the economic and geographical position of the company. It is also worth pointing out that, due to the diversity of operational and local parameters throughout the processes, the definition of clear and systematic steps will lead to a more transparent and reproducible decision-making process. However, even when dealing with similar companies, the premises are often unique to each project. This, in turn, renders the elaboration of a single methodology to be applied in different sectors very difficult or even impossible. Hence, the diversity of scenarios for decommissioning projects in the same area is essential and should be carefully evaluated.

Due to the maturity of some economic activities, and the relatively short time span of others, the demand for decommissioning processes has been rising steeply over the last years. That rise has been particularly significant in the oil and gas sector [59; 30]. Since that sector often involves large amounts of investment, a careful process for considering decommissioning alternatives is needed. In addition, since we are dealing with an economic activity that affects many other sectors and disciplines, a careful mapping of the stakeholders is required, and full consideration must be given to their needs and concerns. Furthermore, the impacts of the decommissioning activities must be considered in relation to a variety of factors which, in turn, may be relevant to a variety of scientific fields and disciplines. All in all, one can see that these considerations add up to an extremely complex, multidisciplinary decision-making process. It is this process that this paper seeks to address.

Within the oil and gas sector, decommissioning generally involves a multitude of stakeholders in a variety of fields [140]. Government bodies, regulatory agencies, non-governmental organizations, labour unions, operators and oil and gas companies are some examples of the stakeholders involved. In addition, many aspects of the decommissioning activities must be accounted for. Often, *technical*, *environmental*, *social*, *economic*, and *safety* issues are considered, as suggested in the influential guideline in [110].

Due to both the problem complexity and the need to involve several stakeholders — often with conflicting interests — a tool that is able to assist the decision-making process becomes essential. Specially tailored for such problems, multi-criteria decision analysis (MCDA) methods can be a natural fit for decommissioning problems [57], especially in the oil and gas sector. There are also other modeling alternatives, such as *multi-objective programming (MOP)* [42].

This paper aims to review the existing methods for comparing decommissioning alternatives. Another objective is to identify the most common criteria and sub-criteria employed in the literature regarding decommissioning projects in the oil and gas sector. Finally, we also seek to identify research gaps and opportunities for future innovations.

The remainder of this paper is organised as follows. Section 2 introduces decommissioning processes. Section 3 features a brief overview of the main multi-criteria decision analysis

(MCDA) methods. Section 4 covers their application to decommissioning problems, while Section 5 provides an overview of the set of criteria applied within oil and gas decommissioning processes. Next, Section 6 offers a summary of the literature and related research opportunities. Finally, Section 7 presents concluding remarks.

2. Decommissioning processes

Before setting up a project, one generally evaluates its economic feasibility and expected returns over time. These returns tend to increase after the onset of the project and eventually start to decline, up to a point where the project is no longer economically attractive. At this point, decommissioning activities often have to be carried out. In some industries, decommissioning is already accounted for in initial technical and economic evaluations.

Perhaps because of the sensitive nature of the supply, the decommissioning of nuclear power plants is the object of a vast body of literature [e.g., 149]. In the light of recent accidents, the environmental aspects, as well as the risks associated with nuclear generation, are receiving considerable attention in the literature [147; 149]. The decommissioning process is particularly important because of the rather sensitive decisions regarding the final destinations of various radioactive substances. Such substances require specific protocols and specialised management processes, as well as the application of decontamination techniques. In addition, the dismantling of structures should be planned in advance [e.g., 114]. For a historical analysis of the main parameters that influence decommissioning decisions in the nuclear sector, we refer to [149].

Because of the variety of factors to be considered, evaluating strategies for nuclear decommissioning may be a daunting task [114]. One can find in [114] some remarks on the difficulties underlying such an evaluation, as well as a detailed statistical analysis of the relation between a set of indicators and the selected decommissioning strategies. The authors argue that the correlation between some major accidents and premature decommissioning imposes the need for detailed planning to be carried out a priori. With another focus, Paim and Yang [114] assess the challenges and achievements related to nuclear decommissioning laws in Brazil and in Japan. In contrast, Yun-huan et al. [166] make an economic analysis of nuclear dismantling in China.

As previously mentioned, the radioactive nature of some materials imposes some concerns regarding decommissioning strategies. A study on the radiological impact of decommissioning strategies can be found in [153], whereas an analysis of a technique for the decontamination of solid radioactive materials is presented in [119]. Covering a related topic, Mostecak and Bedekovic [104] are interested in the applicability of dismantling strategies that include recycling and reuse of radioactive metal waste. More specifically, in [123] one finds a study of possible processes for the reuse of prefabricated elements in thermonuclear fusion reactors. Finally, [151] features a study of the implementation of a nuclear material measurement technology. The paper presents results related to contamination mapping, waste release measurement and temperature sensing.

Decommissioning is currently a very relevant area of interest within the energy sector. For two examples of literature dealing with wind farms and solar power, we refer to [161] and [74], respectively. Indeed, wind and solar power generation have become more common and gained importance around the world [e.g., 141], which anticipates an increased demand for decommissioning activities in these sectors in the near future. Perhaps because they are pioneers in the deployment of a recent technology, offshore wind farm operators are often concerned with improving the efficiency of the generation, thus relegating the analysis of end of life processes to a secondary role [161]. Such an analysis, however, may be needed in the near future, considering the typically short life cycle of wind turbines, which is around 20 years, as reported in [150]. In addition, the analysis becomes particularly important if one considers the environmental impact of the operations and the large investments required. A useful analysis can be found in [150], where an optimisation method for wind turbine design is devised with a view to reducing decommissioning costs at the endoflife. A related analysis is presented in [144] which highlights the necessity of identifying a suitable end-of-life for solar panels. The authors also discuss the change of raw materials, with a view to improving the efficiency of the production process.

When it comes to the mining sector, decommissioning is mainly concerned with the chemical treatment to be applied in order to avoid the pollution of the soil with metallic materials. The process of reversing the on-site and off-site impacts of the exploration phase is referred to as *mine closure* or *mine reclamation* [7]. Such impacts are often categorized as environmental, economic and social. These categories, in turn, encompass factors such as health and safety, pollution, unemployment and loss of community services and facilities, among others.

Within the transport sector, there is also a concern with finding an adequate final destination for vehicles [141], submarines [72] and aircraft [62], among others. One particular challenge is to find a suitable endoflife for hazardous construction materials which are no longer used, but have been allowed under previous regulation and may currently pose both environmental and health-related risks [158]. Therefore, a critical analysis of the generated waste is needed at the time of decommissioning, with a view to finding an adequate recycling or a sustainable development process. The decommissioning of roads also involves mechanisms to mitigate future habitat degradation. The aim here is to increase the likelihood of survival of endangered species [154]. At the operational level, it can be argued that proper road management can mitigate the environmental impact of the road system by limiting chronic erosion and reducing the risk associated with large-scale events [160].

Considering that the impact of decommissioning decisions and end of life management goes farther than just the industrial environment, it is essential that industries properly consider the perspectives of distinct stakeholders with regards to different courses of action [25; 97; 15; 125; 29]. Indeed, discussions with respect to end-of-life activities have already been undertaken by producers, consumers and authorities. Such discussions can be seen as the result of increased environmental and social pressures [97], a social awareness of the risks posed by current consumption habits [25] and the growing tendency among countries to hold manufacturers responsible for the end of life management of their products.

This paper is focused on the evaluation of decommissioning activities within the oil and gas sector, whose first registered decommissioning processes date back to the 1970s [30]. It can sometimes be argued that keeping the decommissioned structure *in situ* may be an appealing alternative, for example when it can be turned into an artificial reef [33; 141]. At other times, full removal may be not a recommended course of action when environmental aspects are considered, even if it is required by law [80]. In any case, decisions regarding the final destination of decommissioned assets should be carefully considered, taking into account the perspectives of stakeholders and the impact of the decisions on future generations.

Currently, the challenge of reaching a sound decision on the final destination of assets is deepened by the increased demand for decommissioning in complex environments, involving multi-part platforms and sub-sea systems installed in deep water [28; 116]. Hence, there is a relatively urgent need for profound discussions on the subject [21]. However, information availability remains an issue and specialized labour is sometimes scarce due to the recent developments in the field. In Brazil, for example, where deepwater exploration is very significant, one can argue that decommissioning activities are still a novelty and the lack of expertise is evident [103]. Such a combination may lead to a long, unpredictable and bureaucracy-driven decommissioning processes.

2.1. Decommissioning of oil and gas production facilities

The decommissioning process generally takes place when producing from an oil or gas field becomes uneconomical. Decommissioning is often a time-consuming process in the oil and gas sector. This is partly because it may involve the partial or total removal of very complex structures, and partly because it is subject to many regulations from different government bodies. For example, Hamzah [59] reports an estimated duration of three to six years for the whole process in the United Kingdom, while also arguing that the process can take much longer in countries with underdeveloped legal frameworks and less technical experience.

As previously mentioned, decommissioning decisions involve multiple stakeholders. As such, these decisions are politically sensitive and multidisciplinary in nature. The economic and environmental impacts alone involve a large number of interest groups in a variety of sectors, such as the fishing industry, the tourism industry and shipping companies. In addition, the environmental aspect also attracts the attention of civil society organizations directly related to the field. Given that these and other stakeholders possibly have conflicting interests, one is left with the problem of finding a framework to guide the decision-maker to a sound decision, and multicriteria methods are a natural fit [50; 61; 107].

According to the literature, the major environmental issues in decommissioning are the potential effects in the marine ecosystem; the appropriate use and containment of hazardous substances, including naturally occurring radioactive material (NORM) and waste management, which includes finding a final destination for the debris accumulated over the life cycle of a piece of equipment [5; 33; 146; 78]. For an analysis of the impacts of oil pipelines in the fishing industry in the North Sea, in particular, we refer to [129].

Another complicating factor in decommissioning decisions is the fact that the service providers are currently very fragmented. This results in the absence of dominant players, and may be one of the reasons for the lack of consensus on the techniques that should be employed. Such an environment undermines the efforts by offshore oil and gas companies and service providers to come up with accurate predictions of the costs and risks associated with decommissioning activities [65].

World experiences

According to BSEE [24], the Gulf of Mexico had 2,165 rigs in 2016, and 174 of them were decommissioned in that year. Of the decommissioned platforms, most operated in offshore fields at depths lower than 400 ft. The North Sea, another mature exploration area, included 23 fields being prepared for decommissioning in 2017 [111]. According to the same reference, an estimated 800 million pounds will have been spent on decommissioning activities in that area by 2021 . In 2016, there were 1,357 platforms in the area and 157 were decommissioned in that same year; additionally, the estimated number of units to be decommissioned between 2017 and 2025 is 205 [111]. The average age of the rigs in the North Sea is over 20 years. More specifically, the average age of UK platforms is 26 years, whereas Norwegian platforms are 24 years old on average [5].

In Brazil, according to official estimates, 40% of the offshore production units have been operating for more than 25 years. Meanwhile, units aged from 15 to 25 years account for 15% of the total. Up to 2017, only six offshore fixed platforms and five floating production units were decommissioned [103].

To sum up, one can see that a large number of offshore oil and gas production units around the world are at the end of their useful life, which means that these installations are due to be decommissioned soon.

Technological challenges

One of the main challenges of decommissioning activities is created by the depth of a significant portion of the petroleum reserves. Deep reserves demand larger pipelines to connect wells to platforms, thus increasing the complexity of the logistics. In Brazil, for example, according to official estimates, 34% of the currently offshore production units are at a depth that exceeds 984feet [11]. In addition, one can observe an increase in the number of platforms installed in deep or ultra-deep water, due to the projected exploitation of the large pre-salt reserves. Hence, deep-water and ultra-deep-water decommissioning is soon to become a technological, political and strategic challenge.

In addition to the depth of the water column, another important factor is the distance to the coast, since it increases the costs associated with the transportation of structures, equipment disposal and recycling on land. Distant production units impose enormous challenges on the operators with regards to the planning of the removal of these assets. Hence, the time required for the successful completion of a decommissioning plan can be rather long, which is certainly undesirable considering that the decommissioning process involves significant costs, as well as environmental and regulatory liabilities.

Economic aspects

A singular aspect of the offshore exploration of oil and gas is that, unlike most other productive activities, it demands significant investment in the early years of the project . This period is then followed by a period with large positive cash flows that start to decline at some point. After the decline, offshore E&P projects have a period of inevitable negative cash flow. This last period encompasses all decommissioning activities and involves no further generation of revenue [116].

According to IHS Markit [65], annual global spending on offshore decommissioning is expected to more than quadruple by 2040, and the total amount spent could reach US $210 billion over the next 25 years. It is now a consensus that, in order to facilitate the decommissioning phase, supporting activities should start at the onset of the development of a field. They should then continue up to to the end of the production phase. In the United Kingdom, the detailed and revised decommissioning programe must be submitted by the operator approximately five years before the well production is scheduled to end [69].

Regulation

Regulations are being developed and best practices are being updated, especially for systems that are not yet covered by legislation. Even in countries with less experience in the sector, there is a movement to create specific legislation and best-practice guides. In Brazil, for example, the National Petroleum Agency (ANP) is reviewing Resolution 27/2006, regarding the deactivation of production facilities [103], in accordance with current international decommissioning practices. The agency requires the operator to submit the facility deactivation programe for approval. The programe is comprised of a schedule and detailed plans for cleaning operations, waste disposal and environmental recovery [10].

A report on national regulations deemed to be more mature, namely those of Norway, the United Kingdom and the United States, can be found in [45]. The report also covered two oil-producing countries in Southeast Asia, namely Malaysia and Thailand. In another discussion of the decommissioning protocols in the energy sector, Heffron [60] suggested that the rule of law should study regulations that are still poorly defined. Finally, Murray et al. [106] discuss the importance of the marine industry in decommissioning, specifically its role as a data access facilitator. These industries routinely collect critical environmental data needed for sustainable management of marine ecosystems. For the North Sea, for example, the oil and gas industry has been a dominant presence for over 50 years that has contributed to a wealth of knowledge about the environment. As the industry begins to decommission its offshore structures, this information will be critical for avoiding duplication of effort in data collection and ensuring best environmental management. This paper also summarises what the barriers and opportunities surrounding environmental data sharing are.

In summary, the decommissioning of oil and gas facilities is a relatively new challenge worldwide. Multiple efforts are underway to establish sound legislation, standards and best-practices guides. However, one can safely state that countries still enjoy broad discretion in the definition of domestic regulation for deactivation activities [116].

3. Multicriteria decision analysis

Multicriteria decision analysis (MCDA) is a comparative support tool for the evaluation of competing alternatives involving multiple criteria. It is often applied to aid in the decision-making process when one sets distinct goals to be attained by the selected alternative, as briefly mentioned in Section 1. In short, MCDA provides the decision maker with some tools to select an alternative while taking into account different perspectives [159].

One important thing to emphasise is that MCDA methods are not designed to search for *the best* alternative with respect to all criteria. Instead, they identify compromises in real-world situations when there are conflicting criteria and no such alternative exists. Therefore, the analytic treatment applied is as important as the quality of the available information [105]. The model construction and the method of choice are linked to the decision-making process. Standard approaches include *Analytic Hierarchy Process*(AHP) [133], *Preference Ranking Organization Method (PROMETHEE)* [23], *Simple Additive Weighting (SAW)* [49], *Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)* [63], *Elimination and Choice Expressing the Reality (ELECTRE)* [16] and *Multi-Attribute Utility Theory (MAUT)* [40].

Broadly speaking, MCDA methods can be classified into three distinct approaches [e.g., 132; 159; 115]. The first approach gives rise to the so-called single-criterion synthesis methods, which are based on the additive model. These methods allow compensation between criteria, whereby a certain advantage in a given criterion can counterbalance a given disadvantage in another criterion. In addition, they establish aggregations for setting up a unique score for each alternative. The second approach gives rise to the outranking methods, which are classified as non-compensatory. Finally, interactive methods are general enough to be associated with both discrete and continuous problems. For the most part, multi-objective linear programming methods employ interactive procedures.

Table 1 summarises the main MCDA methods, showing their classification, as well as their strengths and weaknesses. It also lists the available software that can be used to assist in this type of analysis.

These methods are capable of assigning score values and other attributes to the available alternatives. The complexity of the model can be seen as an inherent characteristic of an efficient MCDA method. Ultimately, the techniques applied need to be effective enough to satisfy the decision-maker with regard to the trade-offs and compromises considered.

4. Multicriteria methods for decommissioning studies

Since decommissioning is a complex problem, one can expect it to catch the attention of MCDA practitioners. Indeed, many techniques have been applied to the problem, in the interests of either methodological advances or real-world problem-solving. Nevertheless, in spite of the variety of existing methods, there is a tendency to apply simpler methodologies in real-world applications [e.g., 146; 31]. Often, a single-criterion synthesis approach is preferred, whereby a weighted sum of the score of each alternative under each criterion results in the global score of that alternative. Hence, one can say that the problem is transformed into a mono-objective problem whose objective is to select the alternative with the best global score.

Figure 1 details the decision-making process in decommissioning problems. Such a process begins with the selection of a decommissioning project and ends with the evaluation of the selected decommissioning strategy.

Table 1: Strengths and weaknesses of multicriteria decision methods.

Method	Type	Strengths	Weaknesses	Available software	Main application areas	References
AHP	UBM	It is scalable; its hierarchical structure can easily adjust to fit many complex problems.	It contains too many pairwise comparisons; it might have problems due to criteria and alternatives interdependence; it can lead to inconsistencies between criteria and classification.	MakeltRational, ExpertChoice, Decision Lens, HIPRE 3+, RightChoiceDSS, Criterium, EsyMind, Questfox, ChoiceResults, 123AHP, DECERNS	Corporate and strategic policy, public policy, strategic policy and planning.	[49; 56] [71; 133] [138]
PROMETHEE	O	It requires no assumption about criteria being proportional.	It does not provide a clear methodology for weighting coefficients.	Decision Lab, D-Sight, Smart Picker Pro, Visual Promethee	Environment, business and finance, chemistry, logistics and transportation, manufacture and assembly, energy and agriculture.	[156; 6] [22; 23]
SAW	UBM	It allows compensation between criteria; it has simple calculations and it does not require complex computer programs.	Its final scores do not always reflect the real situation; the result might not be logical.	-	Water resource management, business and financial management.	[87; 98] [120; 124]
TOPSIS	UBM / O	It is simple; the number of steps remains the same regardless of the number of attributes.	It has hard-weighting coefficient attribution and attribute judgement.	DECERNS	Supply chain management and logistics, systems engineering, business and marketing, environment, human resources and water resource management.	[63; 165] [124]
ELECTRE	O	It takes into account the uncertainty and imprecision in the analyses.	Its process and results can be hard to explain; ranking can make it difficult to directly identify the strengths and weaknesses of attributes.	ELECTRE III, IV, Is, TRI	Energy, economy, environment and transport.	[47; 55] [95; 131] [132; 159]
MAUT	UBM	It takes into account uncertainty; it can incorporate references.	It needs many input data; preferences must be exact.	-	Economy, finance, actuarial science, energy management and agriculture.	[8; 27] [49; 48] [54; 79] [83; 113]

UBM - Utility Based Model; O - Outranking.

The steps of the flow chart in Figure 1 are detailed below:

- **Development of a decommissioning process**

  Mapping of existing structures and proposal of feasible courses of action (decommissioning alternatives) for each structure.

- **Identification of stakeholders/literature review**

  Identification of people and organisations that may interfere with or be affected by the decommissioning strategy. Their opinions are very important and may help the

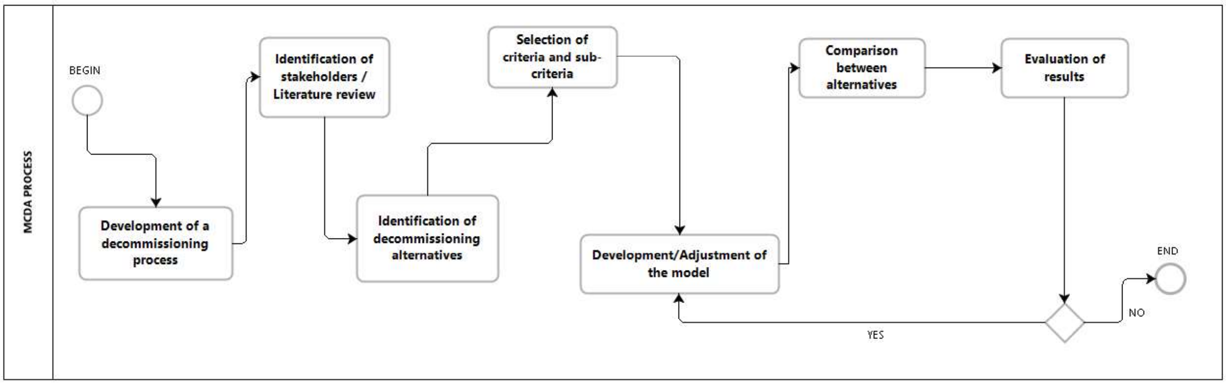

Figure 1: Basic concept of an MCDA process

decision maker select the most adequate decommissioning strategy. A literature review is also relevant for understanding the problem, the available modelling techniques and the potential problems and conflicts.

- **Identification of decommissioning alternatives**

  Mapping of the technologies and procedures available in the market for each possible decommissioning activity.

- **Selection of criteria and sub-criteria**

  Mapping of the indices and variables to be evaluated in connection with each available decommissioning activity. Stakeholders are expected to participate actively in the process of defining the criteria based on which a decommissioning alternative will be assessed.

- **Development/adjustment of the model**

  Proposal for a decision aid tool aiming to integrate multiple criteria in the analysis. The methodology can be further adapted to the specifics of a given case study.

- **Comparison between alternatives**

  Evaluation of each alternative in terms of each selected criterion. The comparison of the evaluations of the alternatives will give rise to an ordering of these alternatives. MCDA techniques are often employed to generate such an ordering, considering that each alternative has pros and cons which are represented by the evaluations with respect to each criterion and sub-criterion.

- **Evaluation of results**

  Sensitivity analysis to evaluate possible changes caused by small adjustments to the model. In other words, one is concerned with evaluating the consistency and robustness of the results obtained.

Figure 2 and Table 2 outline of decision-making tools applied to decommissioning problems, both in the scientific literature and in business reports.

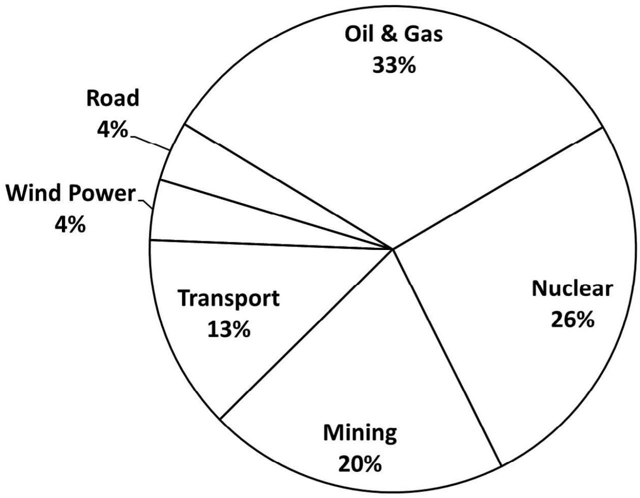

Figure 2: Literature review of decision making for decommissioning by sector

One can see from Figure 2 that the oil & gas (33%) and nuclear (26%) sectors account for the majority of the mapped references. However, the mining (20%) and transport (13%) sectors do not lag far behind.

As Table 2 shows AHP, PROMETHEE, SAW and TOPSIS, in that order, are the top decision-making tools in the academic studies. There are also a small number of references that employ distinct tools, such as decision-tree and goal programming. However, when it comes to business reports, *comparative assessment* is by far the dominant technique. Such a technique, which can be seen as a mono-objective formulation with a weighted objective function, consists of particular methodologies derived from the influential guide in [110].

A detailed review of the principal decision aid techniques applied to the energy sector is presented in the following subsections.

4.1. Applications of the AHP method in decommissioning problems

The AHP is among the tools most commonly applied to energy problems. It has been applied, for example, to evaluate multi-attribute tasks and to assist in nuclear safety training and procedures [96]. Sometimes it is applied in combination with other techniques [e.g., 1]. In the latter study, a facility location problem was solved by means of the combination of a binary method, applied to determine potential areas, and a linear combination approach employed to select candidate areas. In another study, a 3D modelling tool-assisted in the application of the AHP framework to support decommissioning decisions for nuclear installations [88]. As part of that study, a group of experts was requested to fill up forms and assign grades from 1 to 5 to social, technical and economic sub-criteria. Meanwhile, only social and technical aspects were accounted for in the decommissioning problem considered in [77], where AHP and fuzzy logic were combined to reach the results. Like [88], the paper

Table 2: Decision-making methods for decommissioning review

			Decision making methods				
	Reference	Sector	AHP	PROMETHEE	SAW	Comparative Assessment[1]	Others
Articles	Cripps and Aabel [33]	Oil & Gas					SQ
	Fowler et al. [50]	Oil & Gas			✓		
	Henrion, Bernstein, and Swamy [61][2]	Oil & Gas				✓	
	Na et al. [107]	Oil & Gas	✓				
	Kanmkamnerd, Phanichtraiphop, and Pornsakulsakdi [81]	Oil & Gas					NEBA
	Smyth et al. [141]	Wind power					SWOT analysis
	Kerkvliet and Polatidis [86]	Wind power		✓			
	Shaw et al. [139]	Mining			✓		
	Bascetin [14]	Mining	✓				
	Soltanmohammadi et al. [143]	Mining	✓				ELECTRE
	Soltanmohammadi, Osanloo, and Bazzazi [142]	Mining	✓	✓			
	Narrei and Osanloo [108]	Mining	✓		✓		TOPSIS
	Bangian et al. [13]	Mining	✓				
	Dimitrijevic et al. [36]	Mining		✓			ELECTRE
	Masoumi et al. [100]	Mining	✓				TOPSIS
	Amirshenava and Osanloo [7]	Mining	✓	✓			TOPSIS
	Kim et al. [88]	Nuclear	✓				
	Kim and Song [89]	Nuclear					MAUT
	Zachar, Daniška, and Nečas [168]	Nuclear					OMEGA
	Jeong et al. [77]	Nuclear	✓				
	Poskas, Poskas, and Simonis [122]	Nuclear	✓				
	Jarjies et al. [75]	Nuclear					Priorisation methodology
	Ilg, Gabbert, and Weikard [66]	Nuclear					Cost-benefit analysis
	Thompson and Sessions [155]	Road					MIP
	Allison, Sidle, and Tait [4]	Road					Decision tree
	Mergias et al. [102]	Transport		✓			
	Ahmed et al. [3]	Transport	✓				
	Schmid et al. [136]	Transport		✓			
	Zhang and Chen [169]	Transport	✓				
Reports	Xodus [164]	Oil & Gas	✓				
	Repsol [127]	Oil & Gas	✓				
	Shell [140]	Oil & Gas				✓	
	Ineos [68]	Oil & Gas				✓	
	Dunn, Wicks, and Wilson [39]	Oil & Gas				✓	
	Ithaca [73]	Oil & Gas				✓	
	BG Group [18]	Oil & Gas				✓	
	Perenco & Tullow [117]	Oil & Gas				✓	
	CNRI [31]	Oil & Gas				✓	
	Spirit Energy [146]	Oil & Gas				✓	
	ISM [72]	Transport					Scenario analysis
	UoP [158]	Transport					Scenario analysis
	JAVYS [76]	Nuclear			✓		
	Ghosh, Cassidy, and Kozich [53]	Nuclear				✓	
	Wickham, Wilmot, and Phipps [163]	Nuclear					SQ
Thesis	Sudholt [147]	Nuclear					Goal programming
	Martins [99]	Nuclear	✓				

AHP – Analytic Hierarchy Process; ELECTRE - ELimination and Choice Expressing the Reality; MAUT – Multi-Attribute Utility Theory; MIP - Mixed Integer Programming; NEBA - Net Environmental Benefit Analysis; OMEGA – Oracle Multicriterial General Assessment of Decommissioning; PROMETHEE - Preference Ranking Organization Method; SAW - Simple Additive Weighting; SQ - Semi-quantitative and qualitative methodologies; SWOT – Strengths, Weakness, Opportunities and Threats; TOPSIS - Technique for Order of Preference by Similarity to Ideal Solution; [1]Particular methodologies derived from the guide Oil & Gas UK [110] and/or companies; [2]More details in [17].

made use of expert judgement and employed fuzzy logic techniques to aggregate the obtained values. For more details on the combination of AHP and fuzzy logic, refer to [148].

The management of radioactive material was addressed in [122], where the AHP was applied to create a ranking of the available alternatives using both quantitative and qualitative subcriteria. The same technique was employed in [107] to find suitable decommissioning alternatives in the oil and gas sector. To alleviate the computational burden, the authors employed a preliminary screener to reduce the dimension of the platform database. An expert evaluation that made use of the Saaty scale [134] was also applied . The same approach was employed in the analysis of a nuclear plant decommissioning problem in [77]. Finally, Martins [99] used AHP allied to the Geographic Information System (GIS) to select the best spots for the construction of a repository of spent nuclear fuel. The necessary weights were given by stakeholders.

Analyses of end of life alternatives for vehicles that made use of the AHP framework can be found in [3; 169]. In particular, the *Decision Making Trial and Evaluation Laboratory* (DEMATEL) method proposed in [3], makes use of peer-to-peer comparisons between pairs of subcriteria, with a view to reducing their number. In this case, once the subcriteria to be employed were identified, the paper utilised AHP and fuzzy AHP to evaluate dismantling alternatives.

One of the most important considerations in after decommissioning is the recovery of the degraded area. Ideally, it should return to its original conditions. However, sometimes that can be very costly and difficult to achieve. The AHP methodology was also applied in [14] to evaluate options for the end of life management of an open-pit mine.

The reports in [164; 127] also made use of an AHP-based peer-to-peer comparison methodology for decommissioning subsea ducts. Their approach involved qualitative judgements based on quantitative data. The main difference from the traditional AHP methodology is precisely in the use of a qualitative scale, while in the Saaty scale [134], the qualitative judgements are translated into quantitative scales.

4.2. Applications of the PROMETHEE method to decommissioning problems

Introduced by Brans and Vincke [23], the PROMETHEE method has been extensively used in energy sector applications. For example, it was applied to compare energy sources [157], evaluate routes of oil and gas pipelines [152] and select locations for solar power plants [135]. The method has also been applied to solve a number of problems related to waste management, such as assessing final disposal alternatives for electrical and electronic waste [130], solid waste [32] and demolition waste [91]. In the field of decommissioning problems, it was employed to compare end of life alternatives for offshore wind farms [86], vehicle dismantling [136; 102] and mine reclamation [7; 142].

Kerkvliet and Polatidis [86] applied the PROMETHEE framework to aid decision-making in the decommissioning of offshore wind farms. They considered 11 quantitative and qualitative economic, environmental and social sub-criteria, which they evaluated using an ordinal scale. To attribute the weights required by the framework, stakeholders sorted the criteria in descending order of interest, while also admitting the possibility that pairs of criteria might be incompatible. The final method considered linear preference functions but did not produce an indifference threshold. The authors concluded with a sensitivity analysis with respect to the adopted weights.

Vehicle dismantling problems were studied in [102; 136]. Gaussian and linear preference functions were compared in [102], where the alternatives were qualitatively evaluated according to economic, social, environmental and technical criteria. In contrast to Kerkvliet and Polatidis [86], Mergias et al. [102] considered the indifference threshold. We also observe a qualitative evaluation of criteria in [136]. The weights assigned by the stakeholders were averaged and applied in the analysis. It is interesting to highlight the use of the veto threshold for one sub-criterion, namely occupational risks, effectively setting up an intolerance limit for damages to human health. Unlike in the other applications, a distinct preference function was employed for each criterion.

4.3. Application of simple additive weighting to decommissioning problems

Simple additive weighting (SAW) is a simple and intuitive approach, and as such, it has been used in many sectors. It has been applied in the energy sector to select renewable energy sources [26], feeds for bio-gas plants [9] and alternative fuels for vehicles, for example. In the decommissioning field, it has been applied in the nuclear, mining and oil and gas sectors. One of the perceived drawbacks of the method is that it allows for trade-offs between criteria. Hence, special attention should be paid to ensure that sensitive issues, such as environmental and social preoccupations, are not neglected.

The JAVYS [76] report dealt with the decommissioning of a nuclear power plant. It reinforced the importance of complying with legal regulations before a site can be released for unrestricted use. The authors proposed the evaluation of the alternatives by means of a single score comprised of a weighted sum of the evaluations of the criteria.

Seeking to evaluate mine closure alternatives, Shaw et al. [139] made use of an additive aggregation model. An analogous application was studied in [109], which evaluated alternatives for the maintenance of a sterile stack. The sub-criteria were assigned weights from one to five by experts and were later evaluated qualitatively.

In the field of oil and gas decommissioning, Fowler et al. [50] addressed the importance of environmental, social and economic factors in the process of decommissioning, and enforced the importance of allowing a flexible approach capable of encompassing all options and their alternatives. To that end, the paper proposed a multicriteria decision approach, namely multicriteria approval. This approach evaluates trade-offs and directly involves stakeholder groups in the decision-making process.

4.4. Comparative assessment

The influential document in [110] can be seen as the benchmark for decommissioning programs in the field of oil and gas. Many decommissioning reports in the United Kingdom were based upon this guide [e.g., 18; 68; 73; 39; 140; 31]. For the most part, the methods derived from this guide incorporate the specific characteristics of the case study in question. The guide suggests three possible methods for evaluating alternatives. The first is qualitative and based on color scale, while the second and third allow for the merging of quantitative and qualitative analyses. The third method, however, allows the attribution of different weights to the criteria, according to their perceived importance to stakeholders. Generally, the framework underlying comparative assessment is analogous to the SAW methodology [e.g., 68; 140]. However, since the publication of [110], comparative assessment has been regarded as a separate framework.

The British report from Windermere Ineos [68] addressed the issue of selecting an adequate alternative for decommissioning the umbilical system of an offshore oil field by means of comparative assessment. Twenty sub-criteria were evaluated through risk matrices that contrasted the likelihood of occurrence (rare to very probable) with the level of impact (negligible to catastrophic). These measures were obtained from grades assigned by the stakeholders during a workshop. A similar approach was employed in Jacky's report [73] on pipelines and power cables. However, the latter study also included quantitative criteria, such as emissions and cost. In both studies, the final score of each alternative was given as the sum of the average of the sub-criteria scores for each of the criteria.

The BG Group [18] report also followed the guidelines in [110]. Their methodology started with a qualitative evaluation based on a color scale, which was used to prune infeasible alternatives. The alternatives that remain were then evaluated according to qualitative and quantitative sub-criteria. Weights were derived from the evaluation of a panel of stakeholders of the relationships between pairs of criteria, and were then converted into a numerical scale. Another pair of studies in the oil and gas sector were conducted through a workshop that included consultants and stakeholders involved in the decommissioning process [39; 31]. The comparative analysis was performed to provide a balanced analysis of the main alternatives of removal of the substructure of the fields- in this case, total removal and partial removal. Another industry application, this time in the nuclear sector for waste management, was presented by Ghosh, Cassidy, and Kozich [53]. This report also applied a colour-based methodology presented in Oil & Gas UK [110]. A decision tree was elaborated based on this qualitative analysis, which included issues such as waste characteristics and population size.

In [31], quantitative and qualitative evaluations were obtained and transformed into a unitary scale. The qualitative evaluations were attributed to a panel of experts. Another guideline, namely [35], was the foundation behind the analyses within the Bains decommissioning process [146]. Most of the evaluations were qualitative, but some quantitative analyses were also necessary for some criteria, such as cost.

Finally, the influential Brent field report Shell [140] was based on the mixed quantitative and qualitative evaluations introduced in [110]. Arguably the most extensive and elaborate report within oil and gas decommissioning literature, it presents a discussion of the weights and the criteria, and includes a narrative to contextualise the choices contained therein. The report thoroughly detailed the whole process, from the identification of the decommissioning alternatives to the evaluation of each sub-criteria for each alternative. To compare distinct qualitative scores and quantitative indices, the authors proposed a normalized score. Once the weights were assigned, the overall score of each alternative was calculated as the weighted sum of the scores for each sub-criterion. The analysis terminated with a sensitivity analysis of the arbitrary weights attributed to the criteria/sub-criteria.

4.5. Other methodologies applied to decommissioning problems

In addition to the frameworks discussed above, a number of other methodologies are also noted in Table 2. These are briefly reviewed in the remainder of this section.

TOPSIS: In the decommissioning sector, TOPSIS was applied for ranking post-mining land-use possibilities [108; 100; 7]. While [108] focused on sustainability, [7] was concerned with identifying and responding to risks. Finally, [100] focused on the treatment of the uncertainties in the decision-maker's preferences by means of a method combining TOPSIS and fuzzy logic.

ELECTRE: ELECTRE is frequently used to aid in decisions in the energy sector. See for example [94; 46], which aimed to facilitate the selection of energy sources and wind farm locations, respectively. Despite that, when it comes to decommissioning problems, only mine closure studies that made use of this framework were identified [143; 36]. The study in [143] noted that, being an outranking method, ELECTRE allows for the decision-maker to assume that certain pairs of criteria cannot be compared. This is an important quality, given that the problem in question considers many criteria of a qualitative nature.

MAUT: Some decommissioning applications make use of the MAUT framework. Alternatives for decommissioning nuclear reactors and offshore oil and gas platforms were evaluated in [89] and [61], respectively. The utility functions in [89] were established based on interviews with the decision-makers. A comparison between AHP and MAUT in the context of the nuclear sector was presented in [88] The authors' results suggest that a potential drawback of the latter method is the underlying difficulty of generating utility functions for each criterion. On the other hand, the process of generating comparison matrices for each pair of criteria and sub-criteria, which is required by AHP, may be quite cumbersome, especially when there is a a large number of criteria/sub-criteria. As reported in [61], a rather large number of alternatives may be available to decommission a given piece of equipment in the oil and gas sector. Considering all of them in a given study, however, creates increased complexity. Hence, only alternatives that are effectively viable — economically, technically, politically and safety-wise — should be considered. In their analysis, the authors chose to remove some attributes from the analysis, either because of the lack of data or because of the difficulty in evaluating criteria under which alternatives performed equivalently. The required weights were obtained by the swing method, and a sensitivity analysis concluded the study.

Multiobjective programming (MOP): Multiobjective programming has been applied, often in combination with other methodologies to aid decisions in the energy sector. The literature relating to decommissioning problems, however, is rather scarce. A study on autonomous hybrid energy systems and forest fuel treatments made use of the Pareto frontier to unveil the dominance relations between alternatives [118]. Meanwhile, [82] featured a combination of MOP and fuzzy logic to select suppliers, while also accounting for environmental concerns. MOP is particularly frequently employed in the formulation of constraints regarding quality control and capacity, among others. A mixed integer formulation for the decommissioning of highways was proposed in [154] which sought a compromise between cost minimisation and environmental concerns. Other MOP applications in the energy sector were outlined in [126; 58]. The former employed MOP to evaluate the life cycle of

Germany's 2030s energy sector, while the latter considered the trade-offs between cost, profitability and investment in the design of solar power plants. Finally, Sudholt [147] evaluated the dismantling of a nuclear power plant in terms of of goal-programming and sought a trade-off between cost, security risk and project duration. The study utilised the OMEGA model as the main tool, supported by several software applications, such as Matlab, R and AIMMS.

Prioritisation methodology: The *prioritisation methodology* suggested by Jarjies et al. [75] consists in ranking nuclear sites that need to be decommissioned according to a set of prescribed criteria, which are evaluated individually by a decision-making committee. The ranking is later adjusted to take consideration of social, political and economic issues. The first step is the calculation of a quantitative surrogate risk assessment for each facility, based on a multiplicative chain of inventory (e.g radiological risk factor and activity concentration), containment and environmental dispersion (e.g. distance to population and distance to surface water) factors. Each of those factors is divided into value ranges that are related to a score. The second step is called sensitivity analysis, and aims to mitigate the subjectivity of score attribution by arbitrarily adjusting the scores within a Monte Carlo simulation routine. In the last step, the decision committee arbitrarily adjusts the ranking, taking into consideration both the deterministic results and the Monte Carlo simulation.

Cost-benefit analysis: Ilg, Gabbert, and Weikard [66] compared strategies for handling low —and —medium level nuclear waste from a potash mine, which can cause long-term water contamination. The study resulted in the identification of three possible so-called decommissioning options. Here, the selection of the decommissioning strategy was performed by means of a comparison between expected investment costs and expected social damage costs (economic, environmental and health damage costs). In addition, the paper also applied a cost minimisation approach that accounted for the uncertainty regarding the stability of the rock formation and groundwater contamination.

Decision tree: A decision tree is a hierarchical method consisting of decisions and their consequences. For more details about this method, see Rokach and Maimon [128]. It was applied to evaluate the cost-effectiveness of alternatives for the deactivation of a forest road in [4]. The problem was decomposed into several management actions (e.g. deactivating or not the road) and their respective outcomes. This study also included the costs and benefits of the consequences of each event in the decision process.

SWOT analysis: Smyth et al. [141] proposed an ad hoc evaluation of environmental and economic concerns for each decommissioning alternative (partial and complete removal). To support the decision, they employed the SWOT (Strengths, Weakness, Opportunities and Threats) analysis management tool. For more details regarding the tool, refer to Kotler [90]. The analysis is based on previous knowledge, literature and the judgement of specialists. Together with ecosystem services evaluation and in light of the principles for successful and sustainable environmental management outlined in Elliott [43], the authors concluded that the potential ecological, technical and legal issues could be overcome. Furthermore, they suggested that leaving the structure in place would be a better option.

Scenario analysis: This approach is similar to comparative assessment. The difference is that different possibilities for the weights are evaluated and the final decision is discretionary, based on the assessment of the solution for each combination of weights. The approach was applied in [158] to aid the decision on ship dismantling activities. There, the criteria were evaluated one at a time by means of a mono-objective optimization approach, each analysis comprising a scenario. Finally, many combinations of weights also gave rise to different scenarios, whose evaluations were provided to the decision-maker to motivate a final decision. A similar scenario analysis was also applied to support the decision on the dismantling of nuclear-powered submarines [72]. The scenarios were generated by Monte Carlo simulation, taking into account the uncertainties in the assignment of weights to objectives.

Semi-quantitative and qualitative methodologies: Cripps and Aabel [33] ranked alternatives for use and demolition of oil and gas platforms in the North Sea, making use of a semi-quantitative assessment of environmental and socioeconomic impacts. This methodology prescribes degrees of environmental impact. The rationale is to use the scores as a way to classify the alternatives and the impacts associated with each option. Their approach does not explicitly make use of weights, even though users can still rank the results according to their own judgement. Similarly, the report in [163] assessed two options for the decommissioning plan of a nuclear power plant, comparing them in terms of labour, public health, safety, environmental impacts and economic aspects.

Net environmental benefit analysis - NEBA: *NEBA* is a tool frequently applied to evaluate environmental aspects in decision-making processes. So far, it has had limited application in decommissioning problems [81; 162; 38]. One can argue that the application of NEBA to decommissioning studies is still in the early stages. Indeed, it still lacks endorsement by the various regulatory regimes governing decommissioning throughout the world [44].

However, NEBA has emerged as perhaps one of the most useful comparative cost/benefit assessment approaches for weighing the environmental risks, benefits and costs of different plausible decommissioning options [162]. The tool aims to validate the evaluation of response options, and compares the expected response effectiveness with the potential environmental impacts of offshore activities. The ideal output of a NEBA process is the selection of response technique(s) that minimise the overall impacts on the environment and promote the most rapid recovery and restoration of the affected area.

It was applied in offshore jacket decommissioning in the oil and gas sector [81] as a complement to a previous evaluation of decommissioning alternatives that accounted for technical, safety and environmental aspects. Its evaluation was based on the opinion of experts and considered services losses and gains of each alternative in terms of impacts, recovery, benefit duration and post-recovery. The evaluation was founded on the expected deviation from a baseline scenario. The techniques were also applied in [38] as a comparative assessment tool to aid in decisions on drill cuttings piles.

Generally, NEBA is used for comparing and ranking net environmental benefits associated with multiple alternatives to manage oil spills, based on risk analysis [41]. This tool can be incorporated into the project planning phase, as it allows for the assessment of different response strategies to a possible scenario, as illustrated in [64; 34; 2]. It can also be applied to identify response strategies that minimise long-term effects after accidents [52; 20; 145].

Some studies focused on providing input data for NEBA studies [12; 51; 137; 112; 19]. An analysis of the applicability of Bayesian inference in the analysis of net environmental benefit during the oil spill process was presented in [12]. In contrast, Frantzen et al. [51] aimed to identify the long and short-term oil spill effects on Iceland scallops. Another study simulated the influence of the wind in the dispersion of a chemical used for combating oil spills in the German coastal area [137], while a similar work verified the influence of chemically dispersed oil on an amphipod [112]. Finally, the work in [19] focused on Spill Impact Mitigation Assessment (SIMA), which was used to refine NEBA.

4.6. Miscellaneous

Some studies combine frameworks in order to address the shortcomings of a given method or blend distinct approaches.

The main techniques applied in studies related to the energy sector in general, and decommissioning problems in particular, make use of arbitrary weights. Hence, the process of generating these weights becomes an important sub-problem in the studies. An intuitive solution to this problem is to have experts or stakeholders establish pairwise comparisons among the criteria and then apply AHP in the resulting matrix to generate the weights. Such a solution has been applied in a number of studies [e.g., 143; 142; 108; 100; 7]. After the weights are assigned, an MCDA method is then selected for the subsequent analysis. ELECTRE and PROMETHEE were the selected methods in [143] and [142], respectively. Under these approaches, the output is the dominance relation among the alternatives, as established under the method —specific parameters selected by the decision-makers. In contrast, TOPSIS and SAW were both utilised in [108]. TOPSIS was also employed in [7] and compared to PROMETHEE II as a decision aid in a post-mining land selection problem. Finally, fuzzy and TOPSIS were applied together in [100] to solve an analogous problem.

Other case studies are solved under different frameworks in order to validate the results while also comparing the frameworks. As an example, we refer to [36], where a land reclamation problem was solved by means of the PROMETHEE and ELECTRE methods. In this particular study, both methods yielded similar results.

The surveyed combinations of MCDA methods, both for generating weights and validating results, are summarised in Figure 3. Literature that applies two different methods in order to compare final results is highlighted in blue.

5. Criteria considered in MCDA oil and gas models

The articles and reports on decommissioning problems within the oil and gas industry are invaluable sources of information, not only about the models and techniques applied, but also with respect to the adopted criteria. They also provide information on the characteristics

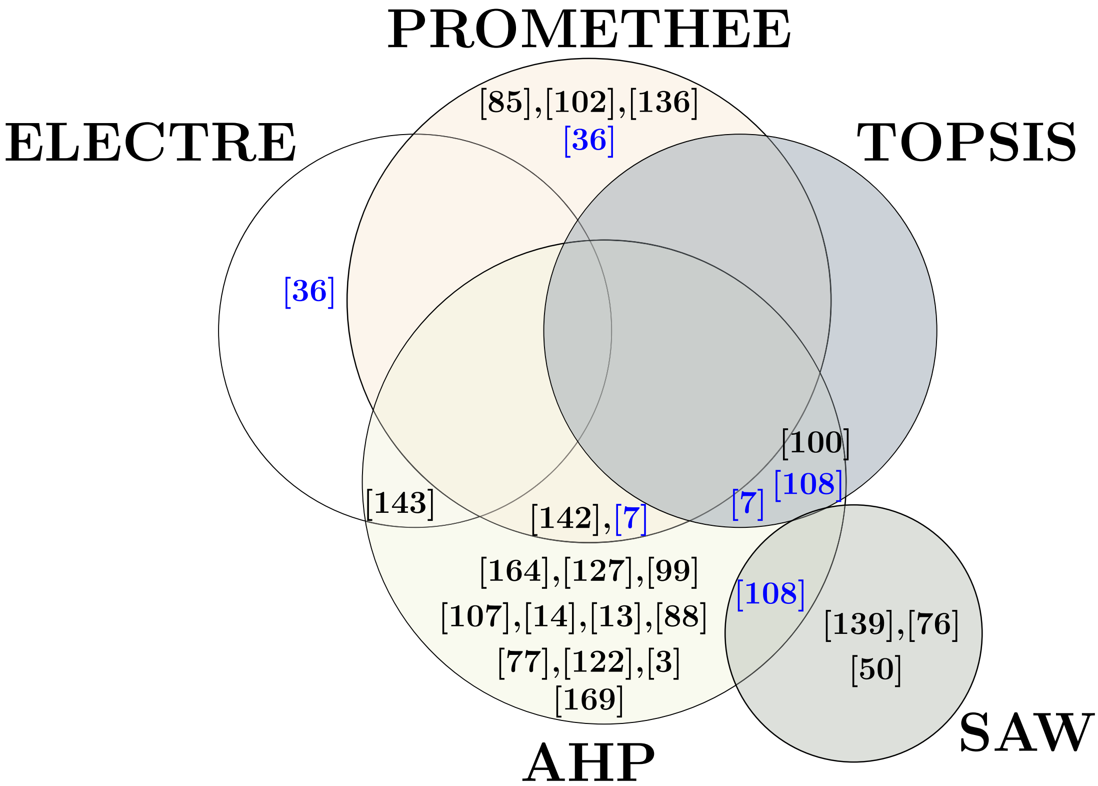

Figure 3: Literature review of MCDA applied to decommissioning, showing works that incorporate different methods

of installations, equipment and structures decommissioned or undergoing decommission, as well as on the decommissioning techniques available at the time of the project.

Tables 3 and 4 summarise the criteria considered in the reviewed studies. The former presents technical, societal, and economic criteria, while the latter outlines their environmental and safety counterparts. The diversity of sub-criteria reinforces the need for multi-criteria decision aids. Perhaps the one exception to that is [107], in which the decision-making process was based mainly on technical aspects, such as structural integrity and platform type.

In order to make the decision process easier to understand, a hierarchical approach including criteria and sub-criteria is generally applied [110]. It is also important to select criteria that are transparent, easily applicable and that cover the major aspects of the problem being studied [67], as perceived by the decision-makers and stakeholders.

Regardless of the criteria selected, it is essential that the results of evaluations be made available to the decision-makers at the onset of the decision-making process [110; 101]. The evaluations can be objective or subjective, quantitative or qualitative, and can be obtained through data compilation, quantitative models, expert panels or stakeholder opinion. It is also important to make sure that the criteria do not overlap or are strongly correlated because, in that case, the decision can be biased. Some common drawbacks of the studies are listed in the literature, such as lack of criteria description, which makes it difficult to understand and interpret the issues contemplated in the criteria; or insertion of irrelevant

Table 3: Oil and gas decommissioning criteria review - technical, societal and economic

		Reports										Articles		
		Repsol [127]	Shell [140]	Ithaca [73]	INEOS [68]	Xodus [164]	BG Group[18]	Marathon Oil [39]	Spirit Energy [146]	CNR International [31]	Perenco [117]	Henrion et al. [61]	Fowler et al. [50]	Na et al. [107]
Technical	Technical feasibility	✓	✓	✓	✓	✓		✓		✓	✓			✓[1]
	Risk of major project failure				✓		✓		✓		✓			
	Ease of recovery from excursion									✓				
	Technology demands/track records						✓			✓				
	Weather sensitivity			✓	✓						✓			
	Platform type[2]													✓
	Weight management[2]													✓
	Logistics requirements[2]													✓
	Structural integrity[2]													✓
Societal	Recreational fishing acess												✓	
	Effects on comercial fisheries	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Residual effect on navigation or other access											✓	✓	
	Employment		✓			✓			✓				✓	
	Impact on communities	✓	✓	✓	✓		✓	✓	✓	✓	✓			
	Taxation concessions												✓	
	Economic stimulus												✓	
	Cultural impingements												✓	
	Public access												✓	
	Public sentiment												✓	
	Diving opportunities												✓	
	Clear seabed												✓	
	Unobstructed ocean view												✓	
	Amenities[3]									✓				
Economic	Residual liability including monitoring and remediation if necessary			✓	✓						✓			
	Liability for property damage												✓	
	Liability for personal injury												✓	
	Cost risk and uncertainty						✓							
	Replacement of construction materials												✓	
	Landfill												✓	
	Onshore processing												✓	
	Personnel												✓	
	Mobilisation of support vessels												✓	
	Cost	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		

Merged cells represents a single criteria that correspond to the others indicated.
1 In this article, the subcriteria are part of 'logistics requirement' criteria.
2 [107] covers only technical criteria. Those criteria are subdivided into 20 sub-criteria.
3 The risk from any near-shore and onshore operations and end-points on any aspect of the amenity or infrastructure of the environment.

Table 4: Oil and gas decommissioning criteria review - Environmental and Safety

		Reports										Articles		
		Repsol [127]	Shell [140]	Ithaca [73]	INEOS [68]	Xodus [164]	BG Group[18]	Marathon Oil [39]	Spirit Energy [146]	CNR International [31]	Perenco [117]	Henrion et al. [61]	Fowler et al. [50]	Na et al. [107]
Environmental	Operational environmental impacts		✓							✓				
	Production of exploitable biomass												✓	
	Legacy environmental impacts		✓				✓							
	Effect on water column								✓					
	Alteration of trophic webs												✓	
	Alteration of hydrodynamic regimes												✓	
	Facilitation of disease												✓	
	Waste								✓					
	Impacts of end-points[2]									✓				
	Proportion of material recycled			✓										
	Proportion of material landfilled			✓							✓			
	Contamination												✓	
	Seabed disturbance and/or habitat alteration	✓		✓	✓	✓			✓		✓	✓	✓	
	Hydrocarbon release from pipelines			✓	✓						✓	✓		
	Chemical discharge	✓		✓	✓	✓					✓	✓		
	Accidental spills	✓			✓	✓	✓	✓				✓		
	Noise underwater and onshore	✓		✓	✓	✓	✓	✓						
	Conservation species	✓		✓		✓	✓	✓	✓			✓[1]	✓	
	Conservation sites	✓		✓		✓	✓	✓	✓		✓		✓	
	Protection from trawling												✓	
	Spread of invasive species												✓	
	Estimated discard to sea										✓			
	Energy use	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	
	Gaseous emissions	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Safety	Safety risk to offshore project personnel	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
	Safety risk to onshore project personnel	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
	Safety risk to other users of the sea[3]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
	Residual risk to third parties[4]	✓		✓	✓	✓	✓				✓			
	High-consequence events	✓				✓	✓						✓	
	Exposure to toxic construction materials												✓	
	Exposure to drilling mud												✓	
	Risk to divers during decommissioning operations			✓	✓						✓			

Merged cells represents a single criteria that correspond to the others indicated.
1 Separate sub-criteria for marine mammals and marine birds.
2 The impacts of offshore and near shore end-points on any aspect of the marine environment. Impacts of onshore end-points on any ecological aspect of the terrestrial environment.
3 The risk that each decommissioning option poses to other sea users. These might include fishermen, shipping crews and others .
4 The risk that each decommissioning option poses to third assets and vessels. These can include pipelines, cables, support vessels etc.

or very similar criteria. For further details, refer to [110; 101].

An approach to tackle the potential overlap of criteria was proposed in [92]. This study introduced boundary conditions intended to exclude *i)* irrelevant criteria, which present similar evaluations for all alternatives; *ii)* criteria whose evaluation lacks actual or estimated data; *iii)* criteria that present a very large degree of subjectivity (e.g., the *value* of ocean landscape preservation will largely vary depending on the stakeholder's perspective) and *iv)* criteria whose evaluation is too small to make any difference. The criteria that made the selection process were inputted in the comparative tool described in [61].

Despite the consensus regarding a relatively large set of criteria and sub-criteria [e.g., 110; 35; 101], regional issues may add an invaluable element. Accordingly, the decision-maker should carefully consider the additional criteria and sub-criteria that are particularly relevant to a given region. The underlying characteristics of a given decommissioning process may also give rise to distinct criteria and sub-criteria. For instance, decommissioning sub-sea structures is rather different from decommissioning a topside structure. Hence, it is only natural that a subset of the (sub)criteria will differ from one to the other. Nevertheless, it should be mentioned that the influential recommendations in [110; 35] led to a certain degree of standardisation of the sub-criteria set, particularly in British technical reports. Table 4 illustrates, for example, the nearly universal adoption of the sub-criteria "safety risk to offshore project personnel" and "effects on commercial fisheries".

6. Research gaps and opportunities

The literature review demonstrates that many efforts have been made to improve the decision-support methodologies in decommissioning processes. Especially in the oil and gas sector, legislation and guidelines have been elaborated [e.g., 140; 101; 37], mainly in developed countries and in consolidated exploration areas, such as the North Sea and the Gulf of Mexico. However, there is still a need for a robust methodology for deep and ultra-deep waters.

The basic criteria to be analysed in the methodology appear to be already consolidated, as mentioned in Section 5. However, it is important that the decision-makers pay attention to the peculiar characteristics of each project. The best option is to select and evaluate the sub-criteria on a case-by-case basis, considering the singularities of each project.

Despite the advances made, several research gaps and open problems remain. To the best of our knowledge, no investigation has been performed to detect overlap and correlation among criteria in oil & gas industrial cases, despite the existing guidelines [110] and recommendations in the literature [167; 84; 92]. Therefore, we recommend the development of standard guidelines and methodologies aimed at avoiding the definition of correlated criteria. The dependencies and correlations should be checked a priori, in order to avoid multiple evaluations of the same phenomenon.

In terms of subcriteria analysis, it is important to incorporate uncertainty into the judgement of both qualitative and quantitative variables. It is clear from the literature review that the main methods that have been applied for uncertainty treatment are fuzzy logic [e.g., 77], Monte Carlo simulation [e.g., 61] and linguistic terms [e.g., 146; 73]. The overall performance evaluation can be very sensitive to the local evaluation of certain criteria. Therefore, identifying how these variations can change the final decision is crucial for defining a robust methodology.

Additionally, the weight assignment is usually arbitrary, often making use of the opinions of specialists [e.g., 86; 158]. One can use AHP to convert pairwise comparisons into a set of weights [e.g., 143; 142; 7]. Such a process involves considerable subjectivity, and could benefit from a standard guideline on weight attribution.

To mitigate the drawbacks of arbitrary weight attribution, authors often resort to varying the adopted weights within a sensitivity analysis routine [e.g., 140; 61; 86; 136]. These routines, however, can be very limited, due to a poor exploration of the possible weights to be assigned. Indeed, the analysis generally consists of varying the weight of a single (sub)criterion at a time, considering only a small number of possibilities. This can result in poor exploration of the high-dimensional space of weights, which, in turn, may increase the risk of making a biased decision. Methods able to identify how changes in the multi-dimensional space of weights affect the selection of the decommissioning activities would certainly contribute to the development of the field. Since we are dealing with high-dimensional spaces, machine learning techniques could be explored.

Finally, decommissioning activity is projected to undergo significant growth between now and 2040 [70]. Such growth should be accompanied by the development of flexible laws and regulations, with a view to promoting a better environment for the operators. Currently, the market is very fragmented [65]. The activity needs to be denser and involve a greater amount of skilled labour so it can be carried out effectively.

7. Concluding remarks

The end of life of oil and gas exploration structures has become a worldwide concern, and the focus of many discussions involving regulators, companies and government entities. The objective is to generate sound guidelines regarding the selection and adoption of decommissioning strategies. This article analyses decommissioning in multiple economic sectors, with a focus on oil and gas. It summarises the methods that have been used for decommissioning decision-making, as well as the criteria that have been selected to guide the decision process within the oil and gas sector.

Due to the large number of actors interested in decommissioning in the most diverse areas, it is important that multiple criteria be analysed in order to make a decision. It is generally agreed upon that the selected criteria should cover economic, environmental, technical, social and safety concerns. Regarding the subcriteria, it is important to highlight that each problem has its peculiarities. As a result, it should be clear that subcriteria are not necessarily the same for different localities. In order to properly account for local factors, one should consult with the stakeholders and conduct a thorough literature review.

MCDA methods are confirmed in the literature as powerful tools to address complex decision-making problems. Although other methods, such as cost-benefit and decision trees, can also be applied to decommissioning problems, MCDA is widely applied to support decommissioning decisions, as it has the advantage of aggregating views from different stakeholders. In view of the diversity of decommissioning options and the potentially large number of alternatives associated with each one, developing a model and adjusting its parameters is essential to attaining better results and to promoting transparency. Such a model may demand multiple techniques and tools in order to address the complexity of the problem.

The review emphasised that AHP is one of the most-used methods for decommissioning decisions in many areas [93; 121]. It is a simple technique that generates global scores for each alternative, and it is generally used as a secondary tool for weight attribution. There is also frequent application of outranking methods, such as PROMETHEE, which are used to translate the preference relations established by decision-makers.

In addition, technical reports tend to use their own methodology to select an appropriate alternative for decommissioning offshore installations, called comparative assessment. The comparative assessment guideline for decommissioning programs [110] has been used as a basis for multiple approaches. It is generally similar to the SAW method, and is based on the opinions of stakeholders. The method is intuitive, with simple calculations, and can be performed without complex software. However, it is a simplified technique, which allows compensation between the criteria, and may fail to integrate multiple preferences. It is expected that the forthcoming work will improve decommissioning decision-making techniques.

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